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MATERIALS INTEGRITY PROJECT : A REVIEW OF 1984 AND PROPOSALS FOR 1985

Report No 85-9-K

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ABSTRACT

This report outlines the work programs performed in 1984 by the Materials Integrity Project of the Metallurgical Research Department. A list of reports issued, external publications and seminars is presented. The direction of the 1985 work programs is outlined. The main thrust of these programs will be in the area of CANDU core components although it is anticipated that some work will continue in support of the fossil fired generating stations.

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EXECUTIVE SUMMARY

MATERIALS INTEGRITY PROJECT : A REVIEW OF 1984 AND PROPOSALS FOR 1985

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Metallurgical Research Department

The Materials Integrity Project is responsible for metallurgical problems related to CANDU reactors and also thermal plant generating stations. In 1984 a variety of projects were performed and some key results obtained are:

i) hydride blisters can form on Zr-2.5 wt% Nb pressure tubes. This work is related to the overall Tube Response After Contact (TRAC) program.

ii) Irradiation growth of Zr-2.5 wt% pressure tubes indicates that texture is not necessarily the primary factor which determines growth direction. Some specimens in the Dido reactor have now reached fluences of 5×10^{25} nm^{-2} which is approaching the levels of pressure tubes in PGSA-3 and 4. The Dido specimens should start to "overtake" pressure tubes by the end of 1985.

iii) Biaxial deformation of pressure tubes for LOCA analysis has been performed both in inert and steam environment. Heating rates of up to 25 K s^{-1} have been used.

iv) Transmission electron microscopy of Zr-2.5 wt% Nb pressure tube materials has revealed that <c> component dislocations are present in low angle sub-boundaries. These dislocations may have a significant impact on the irradiation growth characteristics of these materials.

v) Residual life studies of thermal plant components were "expanded" through the initiation of a collaborative program with the CEGB.

vi) Corrosion fatigue facilities were developed for crack initiation studies.

An outline is also presented of the 1985 work programs of the Materials Integrity Project.

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To Mr. F.J. Kee
Director of Research

MATERIALS INTEGRITY PROJECT: A REVIEW OF 1984 AND PROPOSALS FOR 1985

1.0 INTRODUCTION

In March 1984 the Nuclear Metallurgy Unit of the Metallurgy Section and the Thermal Plant Unit of the Corrosion and Thermal Plant Section were amalgamated to form the Materials Integrity Project.

In 1984 there was still significant work related to the PGSA-2 pressure tube rupture which occurred in 1983. As a result of this incident an integrated study was identified to evaluate Zr-2.5 wt% Nb pressure tubes which contact their calandria tubes. The program is identified as TRAC [Tube Response After Contact] and considers the growth of hydride blisters on both small and large scale specimens. The aim of the program is to determine if blisters can form on Zr-2.5 wt% Nb material and if blisters can result in fast fracture of the tube. Some of the specimens in the irradiation growth program in the Dido reactor at Harwell are close to the same fast (E>1 Me V) neutron fluence level as pressure tubes in PGSA-3 and 4. By the end of 1985 these specimens will start to "overtake" the pressure tubes in terms of accumulated fast (E>1 Me V) neutron fluence. A total of nine TG3 pressure tubes were installed in Bruce Unit 8. The elongation of these tubes will be monitored to determine which production route results in the lowest elongating tube.

Studies on Zircaloy-2 pressure tubes for the REFAB of PGSA 1 and 2 were completed although the decision was taken to retube these Units because of the rupture of G16.

Long-term research is largely dependent on the outcome of Transmission Electron Microsccopy studies. Of particular interest is the presence of <c> component dislocations in low angle boundaries. These dislocations could have a significant influence on irradiation deformation.

In Thermal Plant programs a collaborative study with the CEGB was initiated on residual life. This study involved the attachment of a Research Officer from the Berkeley Nuclear Laboratories to the Materials Integrity Project.

2.0 MATERIALS INTEGRITY PROJECT PERSONNEL

Project Manager	Dr. R. Fleck
Irradiation Deformation	Dr. J. Parker
Core Component Materials Properties	Dr. E. Ho; Mr.M.McGraw/Mr.A.Donner
Hydrides and Hydride Cracking	Dr. M. Leger; Mr. G.Shek; Mr. W. Lee; Mr.H.Seahra/ Mr. P. Vesely/Mr.O.Kiir
Residual Life - Thermal Plant	Dr. J. Parker; Mr. Z. Grosdanovski/ Mr. D. Oad
Thermal Plant Metallurgy	Dr.H.J.Westwood; Mr. R.E. Irwin
TEM	Dr. V. Perovic; Dr. A. Perovic; Mr.R.Jarochowicz.

3.0 1984 REVIEW

3.1 Hydrides and Hydride Cracking in Pressure Tubes

3.1.1 Hydride Blisters

Throughout 1984 significnat technical input was given to the Failure Analysis Group and Working Group 2 in relation to the pressure tube failure in PGSA-2 which occurred in August 1983. Prior to the decision to re-tube PGSA 1 and 2 a detailed assessment of the possibility of pressure tube fragmentation was performed.

The Tube Response After Contact (TRAC) program was initiated in 1984. This program is to assess the integrity of Zr-2.5 wt% Nb pressure tubes after they contact their calandria tubes. It is designed to determine if the same type of failure can occur in post PGSA-2 reactors as occured in PGSA-2 in August 1983. The blister growth experiments in OHRD were initiated and also technical administration of the total TRAC program (~$1 M in 1984) was provided.

Blisters have been grown in sections of Zr-2.5 wt% Nb pressure tubes under a variety of conditions. The results to date indicate that blisters have significant hardness gradients through their volume which probably reflect compositional changes. Optical metallography was used to evaluate the time dependence of blister development. The tests also indicated that a critical temperature difference between hot and cold zones of the pressure tube is required for blister initiation even when the hydrogen concentration is above terminal solid solubility. This result has led to the modification of the blister growth model to include hysterisis in the TSS on dissolution and precipitation. A number of blisters have been grown and used in a variety of studies, such as crack initiation, NDE and transmission electron microscopy.

The technical and financial administration of TRAC has required extensive time commitments. TRAC is progressing satisfactorily. It is expected that within the next four months blister growth dynamics, both experimental and theoretical, will be reasonably well understood. Initial experiments on crack initiation have been performed but it is estimated that six months will be required before an explanation of crack initiation from blisters can be obtained.

Both Queen's University and the University of Toronto have contracts to perform studies related to hydride blisters. These contracts are monitored on a regular basis.

3.1.2 Hydride Crack Growth In PHT Environment

The main objective is to determine if there is any significant effect of PHT environment on the crack growth rate and the threshold stress intensity factor (K) in Zr-2.5 % Nb containing 50 ppm hydrogen. A constant displacement method was employed to generate decreasing K/crack growth data. Baseline tests in air at 250°C produced a projected threshold K of about 10 MPa$\sqrt{m}$ and the crack growth rates at the plateau were within the range previously reported for axial crack velocity. For the simulated PHT environment tests, due to the unavailability of a dedicated autoclave system only limited crack growth data were obtained. The incubation time for delayed hydride cracking was much longer than that in air. This unusual behaviour could be due to the relatively low hydrogen content (43 ppm) in the specimen tested at 250°C. The constant displacement test procedure also limited the range of initial loads that could be applied to the specimen. As the wedge was inserted into the slot of the compact tension specimen, any overloading could blunt the fatigue precrack.

Underloading, on the other hand, would result in either very long incubation or crack arrest. The results suggested that the crack growth behaviour of Zr-2.5 % Nb in aPHT environment is similar to that in air.

3.1.3 Crack Initiation In Pressure Tube Materials

The main objective of this program is to examine the factors that may cause crack initiation in pressure tube material. The prevention of or the reduction in crack initiation can have a significant contribution to the overall reliability of the fuel channel. A brief review of the four major concerns was presented at a work group meeting on fuel channels at WNRE. The current work programs include:(i) constant load cantilever beam tests to examine the effect of hydrogen content and surface finish; (ii) tensile tests to clarify the hydride fracture process;(iii) four-point bend tests to investigate crack initiation at rolled joint; (iv) the effect of water environment on crack initiation. Two specific programs were proposed to extend our understanding of the crack initiation process and to prepare for future data requirements; these are:

Program 1 involves four-point bending of pressure tube sections with increasing hydrogen content. The amount of stress relaxation at test temperture can be estimated from previously reported creep data and the relaxed stress will be about 50% of the original value after about 2000 hours. Monitoring techniques will include acoustic emission and periodic magnetic particle inspection. An estimate of the hydrogen content at the crack initiation site can provide a comparison with results obtained under fixed hydrogen conditions. The program will improve our knowledge of the crack initiation process in individual tubes after about 16 to 20 equivalent power years.

Program 2 is designed to examine the effect of load following on crack initiation. The fatigue loading cycle on a tensile type of specimen will be based on a hypothetical load following cycle. The potential drop system will be used to detect crack initiation in cyclic loaded and static loaded specimens.

3.1.4 Fuel Bundle Scratch Test

The purpose of the program was to examine if fuel bundle wear pads can scratch and crack existing radial hydrides and thus initiate delayed hydride cracks. Hydrides near the ID surface of a curved specimen were reoriented to the radial-axial plane by thermal cycling under stress applied by a four-point bend jig. The extent of reorientation was found to be affected by the surface finish. Specimens with a honed finish contained much

more radial hydrides than specimens with a sand blasted finish, probably due to the effect of residual stresses. Specimens containing a significant amount of radial hydrides at the ID surface were subjected to a severe fuel bundle scratch test. No cracking of the radial hydride was observed by metallogaphy before and after oxidizing the scratched specimen at 800°C. Thus it was concluded that fuel bundle scratches are unlikely to initiate delayed hydride cracking.

3.1.5 Zr-2 Double Torsion Specimens

This is a co-operative program with the Fracture Mechanics Unit to evaluate the fracture toughness of a hydrided Zircaloy pressure tube using small curved specimens. Twenty-two double torsion (DT) specimens were machined from two ring sections taken from a hydrided Zr-2 pressure tube which had been slit burst at room temperature. Fracture toughness of the specimens was determined by four-point loading at room temperature and the results indicated that there was significant variation in fracture toughness among the specimens. Metallography showed that the variation in fracture toughness was due to local difference in hydride morphology at the crack front. Hydrides in the OD region of the Zircaloy pressure tube were more reoriented, probably due to residual stress from tube fabrication. There was significant variation in the size of the OD reoriented zone and the extent of hydride reorientation around the circumference and along the length of the tube. There was fairly good correlation between HCC (Hydride Continuity Coefficient) and fracture toughness. Specimens with high HCC (more reoriented hydrides) had lower fracture toughness. The correlation appeared to be better if the HCC in the centre third instead of the entire wall thickness was considered. Fracture toughness determined from slit burst test was within the scatter band bounded by the DT specimens with similar hydride morphology. This program demonstrated the importance of a statistical or parametric determination of fracture toughness of zirconium alloy pressure tubes containing radial or reoriented hydrides.

3.1.6 Hydride Morphology In Over-Extended Rolled Joint In Zr-2 Pressure Tubes

Information regarding the hydride morphology in a Zircaloy over-extended rolled joint was required to determine the proper notch location of the curved double torsion specimens. Metallography was performed on two hydrided Zr-2 over-extended rolled joints to examine the effects of residual stress on hydride orientation. The results showed that the radial hydride zone covered about 10-13 mm inboard of the burnish mark and its size was not significantly affected by the magnitude of the as-rolled residual

stress (520 and 740 MPa). The hydride orientation gradually became more circumferential further inboard and was unaffected by residual stress from over-rolling about 30 mm inboard from the burnish mark. A series of double torsion specimens was machined from the rolled joint and tested at room temperature. There was a large variation in fracture toughness ranging from ductile behaviour to fast fracture. Several specimens with the extreme behaviour had been examined metallographically and the variation in fracture toughness could be attributed to differences in hydride morphology.

3.1.7 Hydriding Of Zr-2.5 Nb Pressure Tubes

A large effort has been spent on hydriding pressure tube material in support of various programs such as the blister growth studies, NDE evaluation of hydrides, the SPEL test loop on TRAC studies, deuterium diffusion studies, and the University of Toronto's hydride studies etc. We now have the expertise to hydride a variety of specimen geometries to desired hydride concentration and hydride morphology.

3.1.8 Delayed Hydride Crack Growth

Only a few tests were performed during the year because of limited resources in personnel and equipment. The emphasis was on specimens with end-of-life hydrogen concentration, tested at reactor operating temperature. The results showed that the orientation of the hydrides appeared to have little effect on DHC velocity. For specimens with high hydrogen concentrations (80 ppm cracking might occur during the cooling cycle from 300^{o}C to the test temperture. A BASIC program for the computer-controlled data acquisition and control units for the multi-unit DHC tests has been written and tried out. Parts and components (furnaces, temperature controllers) for the construction of the test units have been received and are being assembled.

3.1.9 Fractography Of Zr-2 Compact Tension Specimens

A selected group of Zr-2 compact tension specimens containing different hydrogen concentrations (30, 40, 60 and 100 ppm)and tested at various temperatures was examined in the scanning electron microscope. At high test temperatures in the upper shelf regime, fracture was by ductile shear and there was no cleavage ahead of the fatigue crack. For the 60 ppm sample in the transition temperature region, cleavage of hydrides was observed in the region ahead of the fatigue crack. Further crack growth was by ductile shear. All specimens behaved in a brittle manner at room temperature. SEM showed that the crack path was by cleavage fracture of hydride platelets and ductile shear in

the metal matrix between the hydrides. The amountof shear depends on the number and size of hydrides present in the specimens.

3.1.10 Diffusion Coefficients Of Deuterium in Zr-2.5 Nb-Pressure-Tubes

Data on diffusion coefficients of deuterium in Zr-2.5 Nb pressure tubes are required for hydrogen ingress, blister growth and delayed hydride crack growth models. Deuteride layers were electrolytically deposited on one end of the specimens which were then diffusion annealed at 250°C and 300°C for an appropriate length of time. The hydride distribution and hydrogen concentration along the length of the specimens was determined. Preliminary results showed that the diffusion coefficient of deuterium in the axial direction was about 9.3×10^{-11} m^2/sec at 300°C which followed the mass effect when compared to that of hydrogen (ie DH/DD 1.4). However, the diffusion coefficient of deuterium is a lot closer to that of hydrogen at 250°C. The results also showed that the diffusion coefficient in the transverse direction of the tube is higher than that in the axial direction.

3.2 Irradiation Deformation

3.2.1 Irradiation Growth Of Pressure Tube Materials

A major assumption in the existing design approach for pressure tubes is that contributions from thermal creep, irradiation creep and irradiation growth can be described independently and them summed. Currently, samples are being irradiated in the Dido reactor of AERE Harwell at ∿280°C to provide indications of growth behaviour to end-of-life fluences ahead of the power reactors, to quantify the effect of material variables on irradiation growth, and examine the suitability of materials for the manufacture of future pressure tubes.

Results have been obtained to a fluence of $\sim 5 \times 10^{25}$ $n.m^{-2}$ and indicate that after an initial transient the majority of irradiation growth has taken place under approximately steady state conditions. Current pressure tubes are typical of cold-worked, high dislocation density material, and in these samples positive axial growth has been observed. The rate of growth detected is below that predicted by the current design approach. Material manufactured as part of the TG3 project is also being studied. One classification, Route 1, has shown axial and transverse contraction. This result cannot simply be explained in terms of the usual expression relating irradiation growth to texture.

At year end an extension to the irradiation program was initiated to consider the effect of temperature on irradiation growth. This work will consider behaviour under predominantly isothermal irradiation conditions as well as considering the effect of temperature changes on growth.

3.2.2 Thermal Cycling Of Pressure Tubes

Analysis of stress relaxation tests on transverse section of pressure tubes has been carried out. These results are in broad agreement with published data. Short term tests have indicated that temperature cycling results in greater relaxation than similar tests carried out under isothermal conditions. However, these tests have not been of sufficient duration to determine whether these effects will be observed in service. Analysis of similar testson longitudinal pressure tube samples has been delayed due to staff shortages.

3.2.3 Texture Measurements Of Pressure Tubes

At the time of installation off-cuts are taken from the front and back end of pressure tubes. Texture measurements have been carried out using an X-ray diffraction technique on off-cut material from Bruce NGS, Unit 2. An attempt was made to correlate the observed microtructural differences with variations in tube elongation detected by plant measurements. Substitution of anisotropy factors based on the texture parameters in the current design equation revealed that some general trends in behaviour exist. However, differences in texture between front and back end off-cuts, as well as general data scatter, suggest that the current approach is not able to predict the elongation behaviour of individual tubes.

3.3 Materials Properties for CANDU Reactor Core-Component Alloys

3.3.1 Transient Deformation Behaviour

In the past year, a very limited number of transient deformation tests (ie simultaneous loading and temperature ramping) were carried out. The main thrust of the work in this area was in the development of computer programs for use with the computer-controlled Materials Characterization Test Facility (MCTF). To date, several experimental techniques have been developed and tested for executing a variety of computer-controlled transient deformation testing.

3.3.2 Fundamental Studies Of Elevated Temperature Deformation Behaviour

A test program designed to produce experimental tensile strength data for Zircaloy-2 calandria tube (CT) material as a function of strain rate over the temperature range 295-573 K, was completed. The main purpose of this study was to obtain tensile data which were suitable for use in reactor safety analysis of accident scenarios in which the pressure tubes (PT's) have failed. The more significant results obtained were as follows:

1. The uniaxial tensile strength in both the axial and transverse direction of the Zr-2 CT is strain rate dependent over the ranges of temperature and strain rate investigated.

2. The difference in ultimate tensile strength (UTS) between the axial and transverse directions was small but the difference in 0.2% offset yield trength (YS) was large, with the transverse specimens having the greater YS's over the range of test conditions examined.

3. For all test conditions investigated (295-573 K and 2 x 10^{-4} - 4 x 10^{-1} s^{-1}), the observed limits of uniform strain were much greater in the axial than in the transverse directions of the CT.

A test program designed to produce experimental tensile strength data for Zr-2.5 wt % Nb PT material as a function of strain rate over the temperature range 295-1073 K, was also completed. The main purpose of this work was to obtain data which were suitable for use in reactor safety analyses under a variety of hypothetical accident conditions. The more relevant findings were as follows:

1. Over the ranges of strain rate and temperature investigated, both the axial and transverse tensile strengths are strain rate dependent except in the vicinity of about 600 K.

2. Steady-state strain rate data obtainable from tensile and creep tests are equivalent.

3. The use ofpower law creep equations with constant stress exponents for analysis of general transient deformation behaviour may lead to considerable error.

4. As was the case with transverse Zr-2 CT material, the observed ratios of (YS/UTS) were high and the limits of uniform strain were very low, typically in the range 0.02 - 0.04 for temperatures up to about 750 K.

3.3.3 Biaxial Deformation Behaviour Of Zr-2.5 Wt % Nb PT Material

In the past year, ten (10) biaxial tests were performed. Seven (7) of these tests were done to complete a contract research program funded by AECL-WNRE. The other three (3) tests were carried out as per specifications outlined by NSSD personnel. The pressurizing medium was either inert gas or a mixture of inert gas and steam generated in-situ. Some of the more significant results obtained were as follows:

1. For test pressure in the range 1-4 MPa and constant heating rates in the range 1-25 K/s, the observed average circumferential strain attained at the end of the test or prior to rupture were well in excess of the nominal contact strain of 0.18.

2. Over the time scale of the tests carried out for WNRE, the effect of steam per se on biaxial deformation behaviour appeared to be insignificant.

3. The starting microstructure of the test sample played an important role in determining the biaxial deformation behaviour.

4. Under biaxial deformation conditions, the hoop stress increases much more rapidly with hoop strain than in the uniaxial case because both wall thinning and an increase in tube diameter contribute to increase the hoop stress for a given increase in hoop strain.

5. An internal pressure of 0.25 MPa was not sufficient to produce "contact" diametral strains in a steam environment for temperatures up to about 1410 K and hold times up to 300 seconds.

6. Comparisons of test results with code predictions indicate that the use of the WNRE creep correlation for tempertures above about 1273 K is questionable.

In addition, the biaxial test results obtained provide a relatively large experimental data base suitable for use in the verification of available elevated temperature deformation codes.

3.3.4 High Temperature Deformation Laboratory

The two major test facilities located in the above labortory (ie MCTF and BTF) were further improved by the acquisitions of new support equipment and the development of new computer programs. In particular, the acquisitions of a second RL02 disk drive, another 16-channel 14-bit A/D converter and another 4-channel RS232 interface board have increased the reliability and capability of the lab's data acquisition system significantly. The versatility of the BTF was increased by the development of new computer software for test control, data acquisition, data analyses and plotting of processed data, and by the acquisition of hardware components required to build a programmable closed-loop control pressure circuit. In addition, D-grips for tension testing of both PT and fuel cladding samples, and compression grip for fuel cladding samples have been designed and machined. The miniature D-grips, custom-designed for testing of Bruce-type Zr-4 fuel cladding ring samples, have been tested out using the computer-controlled MCTF.

3.3.5 Evaluation Of Thick Ended Zr-2.5 Nb Replacement Tubes For Pickering Units 1 and 2

The pressure tube replacement program for Pickering Units 1 and 2 plans to retain the use of one existing end-fitting from each fuel channel assembly. This requires the replacement Zr-2.5 Nb pressure tubes to have thicker wall at one end. The thick-end portion of the pressure tubes will receive a smaller amount of coldwork which may affect their mechanical and metallurgical properties. An evaluation program funded by Pickering Engineering was carried out at OHRD and AECL-CO to study the tensile properties, metallurgical properties (texture and dislocation density), corrosion resistance and hydride reorientation stress of the thick-ended tubes. The results showed that the thick-ended tubes have similar corrosion resistance and texture as the current Zr-2.5 Nb pressure tubes. The thick wall portions had lower tensile strengths because of the lower dislocation density. However, they still met the minimum design strength requirement at 300°C. The thick wall region appeared to have higher circumferential residual stress and lower hydride reorientation stress than current tubes. This would make it easier to form radial hydrides in the thick wall region. However, the differences were probably too small to significantly alter the hydride morphology in the thick-ended tubes.

3.4 Transmission Electron Microscopy Studies Of Zr-2.5% Nb Alloys

The research undertaken during 1984 had two objectives: (i) to study development of the dislocation substructure in Zr-2.5% Nb alloys subjected to various thermo-mechanical treatments.

The purpose of these investigations was to obtain more fundamental information on the role of dislocation substructure on the mechanical properties and irradiation growth of the pressure tube materials. In particular, the origin of all dislocation networks which contain dislocations with <c> component Burgers vectors were studied.

(ii) To study hydride precipitation in zirconium alloys. The aim of these studies was to provide further information on the fundamentals of hydride precipitation.

3.4.1 Dislocation Substructure

It was observed that heat treatment after cold working causes rapid development of various low angle boundaries. The majority of dislocation networks or arrays created by recovery after cold working were composed of <a> dislocations forming twist or tilt boundaries.

Besides these networks, additional boundaries were observed which were present before and after cold working, indicating that they were formed earlier in the process of pressure tube fabrication, probably during extrusion. The initial observations of the as-extruded and regular pressure tube material subjected to high temperature deformation have revealed dislocation networks in the α-grains which contain dislocations wth c-component Burgers vectors. There was some indicaton that they were closely associated with the α-β interface.

In order to get more insight into the origin of all dislocation networks which contain dislocations with <c> component Burgers vectors detailed studies were performed on various Zr-2.5% Nb alloys emphasizing the role of the α-β interface. The main results can be summarized in the following way: It has been demonstrated that pressure tube alloys contain different <c>or <a+c> disloctions as a geometrical part of their structure at the intermediate or final stage of their fabrication. These dislocations may have screw, mixed or edge characcters and they are combined with <a> screw dislocations forming α/α low angle boundaries. Initially in the β-quenched structure the <c> edge dislocations serve to preserve a good crystallographic fit between the α and β phases. After extrusion, the dislocation substructure of the α/β interface become much more complicated,

containing additional grids of screw dislocations, in addition to the original arrays of edge <c> dislocations. The structure can be further complicated by arrays of steps in the c and a-directions. The additonal network of screw dislocations accommodate a rotation of the β-phase introduced during extrusion from the optical structure established by the β-phase quenching During high teperature deformation, simultaneously many of the initialy randomly oriented Widmanstatten plates of the β-phase are dissolved leaving dislocation networks behind. These α/α networks preserve the residual misorientation between two neighbouring α-grains introduced during extrusion. These networks are composed of different<c> dislocations and <a> screw dislocations forming various low-angle boundaries having predominantly twist character. The nature of the <c> component dislocations contained in a network depends on the particular boundary. Thus it can be seen that a variety of different low-angle boundaries, which contain a high density of <c> dislocations, exist in all pressure tube alloys. Furthermore, many of these boundaries have regular arrays of steps and/or kinks in the c and a directions. Depending on the density of these steps and/or kinks, the boundary can facet and adopt a lower energy configuration. However, in spite of the complexity and variety of different α/α low-angle boundaries, it seems that there is some regularity in their spatial distribution in the pressure tube material. It is found that the majority of the networks which contain <c>-component dislocations lie on the planes close to the prism or pyramidal orientation. This regularity is controlled by the development of the aligned α-β structure in the pressure tube alloys initially established during extrusion. Due to the strong texture, the majority of the basal poles are oriented in the circumferential direction. The strong texture also indicates that the prism and pyramidal planes are preferentially oriented in the pressure tubes after extrusion and subsequent thermo-mechanical treatments. It is expected that the dislocation substructure may influence properties of the pressure tube material in two important ways. Firstly, they may have an effect on the strengthening mechanisms in the alloy. Secondly, they may also affect irradiation growth. Both of these effects will be investigated in detail.

TEM characterization of the dislocation substructure of routes 2 and 3 of the TG3 pressure tube materials has also been carried out. First preliminary observation of these routes are completed. The main difference in the dislocation substructure in these two materials comparing with route 1 is that the cold work structure is not completely recovered. Thus many of the dislocations introduced during cold work are still entangled or arrayed in semi-perfect walls. This may explain the observed differences in the irradiation behaviour of these three

materials.

A detailed electron microscopy study of current Zr-2.5 wt% Nb pressure tubes has been performed. The results of this investigation showed that the current pressure tube materials are characterized by a high density of dislocations or dislocation networks. The dislocation networks are composed of either <a> component dislocations, or <a+c> and <c> component dislocations. Another important microstructural feature of current tubes is the presence of small ω phase in β-grains.

3.4.2 Hydride Precipitation In Zirconium Alloys

As previously observed, hydride precipitation in fine-grained α/β interface or hydride nucleation is completed. The main results of this study may be summarized as follows: The precipitation of hydride plates in a Zr-2.5% Nb alloy is shown to be sensitive to the prior heat treatment of the alloy. For heat treatments that lead to a facetted α/β two-phase microstructure, the α-β interface is characterized by an epitaxial dislocation array and steps with associated strain fields. For this structure, the nucleation of hydrides is controlled by the defect structure of the interface. On annealing the $\alpha-\beta$ structures below the monotectoid temperature, the retained β phase is unstable, decomposing first to β_{Zr} and ω ultimately to α and β_{Nb}. At the intermediate stage, ie with a β_{Zr}/ω two-phase structure, hydride precipitation takes the form of stacks of small hydride plates confined to channels in the lattice between the ω particles. For both microstructural conditions, the preferred site for hydride nucleation appears to be that which can most effectively accommodate the strains associated with hydride precipitation.

The second project is concerned with the role of internal stresses on hydride precipitation in zirconium alloys. This study is currently in progress and it will be done as a part of a joint program between Ontario Hydro (V.Perovic, M. Leger), AECL-CRNL (S.R. MacEwen) and University of Toronto (G.C. Weatherly).

3.5 Residual Life Studies

Problems associated with creep life assessment rise due to uncertainties regarding long term materials data. Thus, design methods rely on extrapolation of short term uniaxial data and then correlation of this information with a "representative" stress for multiaxially loaded plant components. Constant stress uniaxial and internally pressurized tube tests have therefore been undertaken on 2¼ Cr 1 Mo steel to examine methods of

extrapolating data, to identify correlations between uniaxial and multiaxial test modes, and to develop an accurate and utility-oriented approach for plant life assessment.

Uniaxial Testing: A computer based data logging and analysis facility has been installed in the creep laboratory and the appropriate software has been developed. Short term test results have been analysed using the expression

$$\text{Strain,} \quad \varepsilon = \theta_1 \ (1 - e^{\theta_2 t}) + \theta_3 (e^{\theta_4 t} - 1)$$

where t is time. The well-behaved nature of the θ parameters with respect to stress has enabled predictions to be made of long term behaviour. These predications are in good agreement with the limited available published data and thus the θ projection concept appears to offer a method of deriving creep curves for operating conditions from short term tests.

Multiaxial Testing: Instrumented furnace liners have been installed in the tube test facility and these allow accurate monitoring of the specimen displacement throughout testing. Creep curves have been obtained for several thick-walled tubes tested at different internal pressures and a range of temperatures. These tests indicate the importance of temperature on life since in individual tests the maximum strain accumulation occurred where the test temperature was maintained at only $3^{o}C$ above the average. Furthermore, although the total strain observed was $\sim$10%, the vast majority of this deformation occurred during the last 10% of life, with the creep rate accelerating by over fifty times during the test.

Data analysis shows that correlation of minimum creep rates between the uniaxial and tube tests can be undertaken using a von Mises equivalent stress approach. Similarly, a preliminary study suggests that parameters derived from the primary creep regime of uniaxial tests describe behaviour for the tubular samples. Prediction of tertiary creep is however not so straightforward. Quantification of the strain accumulation in tubular tests gives confidence in the conservative nature of the currently adopted strain limit approaches for life assessment and suggest that more accurate techniques can be utilised based on strain-monitoring.

A collaborative exchange of information with the CEGB was initiated and a research officer from Berkeley Nuclear Laboratories was attached to Research Division for five weeks.

3.6 Performance Of High Temperature Fasteners

The two alloys currently used for high temperature fasteners in Ontario Hydro Plant have been studied. Evaluations have been made of material prior to service and after extended operation with the view to identifying the most desirable microstructure for service application and developing life estimation techniques.

12% Cr Stainless Steel: Variable microstructures have been identified in material prior to service apparently associated with minor changes in heat treatment. This structural variability results in differences in properties. In particular, the creep strength of material used to manufacture replacement fasteners at Lambton GS appears to be lower than found for published data. For ex-service studs a reduction in creep and impact properties has been found. This decline in properties appears to be associated with microstructural changes and a tentative correlation with Chromium Equivalent has been observed. For this alloy, it may be possible to assess performance on a compositional basis, with microstructural checks carried out using hardness or replication techniques.

1 Cr Mo V Steel: Variations in hardness and grain size were detected in batches of 1 Cr Mo V steel prior to service. Short term tests.have indicated that material produced by Atlas Steel to manufacture studs for Lakeview GS has lower creep strength than similar material purchased from the UK. Examination of studs removed from Lakeview after reaching the manufacturer's liftime limit did not reveal creep cavitation or cracking. However, reductions in impact and creep strength were found.

3.7 Dissimilar Metal Weld (DMW) Testing

In tubes operating at high temperatures loaded by internal pressure, the hoop stress is approximately equal to twice the axial stress. However, design codes often allow additional axial loading such that the hoop and axial stresses are nominally equal. Service failures in DMW's have been attributed to the presence of end loads so a range of high temperature tube tests have been undertaken on typical plant weldments in an attempt to quantify weld life. Results show that failure modes are similar to those encountered in service,with axial end load reducing high temperature life by up to an order of magnitude even in cases allowed by design criteria. Joints manufactured using Inconel 182 weld metal lasted two to three times longer than welds produced using an austenitic steel, 309 filler. The data from this test program agree with a life prediction model developed at Research Division.

A collaboration with the University of Waterloo examining the microstructure of the fusion boundary in DMW was initiated.

3.8 High Temperture Crack Growth Studies

The objective of thi research is to generate crack growth data under two shift conditions for structural integrity assessment. The collaborative work with the University of Toronto was completed. The test program included crack growth measurement in compact tension specimens loaded under different frequency, minimum to maximum load ratio, hold time and temperature. Both parent microstructure and a welded structure in 2 Cr 1 Mo steel were investigated. The major difference between the weld and parent metal was the effect of hold time on crack growth rates. With small hold time of one minute, there was no significant change in the crack growth rates when the weld structure was tested. Upon increasing the hold time to 20 minutes, the crack growth rates in the weld material were much greater than that in the parent material. In general, the weld structure is more susceptible to creep damage, and with the increase in hold time the weld structure is expected to perform poorer than the parent microstructure.

The in-house program also achieved the objectives set in 1983. The experimental facility was improved and in-depth analysis of the available crack growth data was carried out. The data logging system for recording the potential drop value per crack extension was modified to incorporate the continuous background counting of the fatigue cycle number. This was accomplished by utilizing the onboard interrupt handling capability of the Apple II personal computer. The experimental program was designed to complement the data base generated at the University of Toronto and to fill in any missing gap during crack growth modelling. However, the test program was disrupted twice due to the breakdown of the MTS system. Successful crack growth tests with different frequency, load ratio and temperature were completed with the in-house equipment. Using identical test parameters, the crack growth data obtained were the same as that collected at the University of Toronto. This observation suggested that there was no variation from laboratory to laboratory due to different equipment or procedures.

Since crack growth experiments are time-consuming and expensive, extrapolation from limited laboratory data is essential for life prediction. Thus various mathematical models which provide analytical representation of wide range fatigue crack growth rates were examined. The hyperbolic sine model showed excellent data correlation for different test frequencies and loading ratios. The stress intensity factor range was used as the stress

state parameters for the model; however the same methodology can be applied to other correlation parameters such as the cyclic J integral which has been shown to be theoretically more suitable for the test data.

To examine the effect of creep on fatigue, the linear damage concept was attempted. Using fatigue data at the test temperature, the amount of crack extension per fatigue cycle was added to the creep crack growth for the creep hold period. The weld structure showed an increase in growth rate in 20 minutes hold test when compared to the parent materials. Both microstructures behaved in a similar manner in the one-minute hold test. Due to the lack of creep crack growth data for the parent material, data for the weld microstructure in quenched and tempered condition at a lower temperature were chosen for the creep fatigue analysis. With the limited information, the linear damage concept provided an upper bound conservative value for creep fatigue damage prediction for the parent material.

When the test matrix was first formulated, the over-temperature acceleration approach was adopted to save test time. Based on the equivalent Larson-Miller creep parameter, crack growth rates for short hold time at 625^{o}C were expected to be the same as those obtained for longer hold time at lower temperature. From the data gathered so far, there is no direct and obvious correlation between the test data at 625^{o}C and the actual material behaviour at the steam temperture of 540^{o}C. The unknown effect of temperature acceleration on the fatigue damage part of the test cycle probably accounted for the difference.

3.9 High Temperature-Bolting - Rejuvenation

This program funded by CEA and carried out by Westinghouse Canada in Hamilton was jointly monitored by Manitoba Hydro and Ontario Hydro. The main objective of this investigation was to examine the effect of reheat treatment Hot Isotatic Processing on both materials exposed to high temperature service environment. The program has been completed and a draft report is expected to be received in early 1985. The research effort was initially directed to the characterization of serviced bolts discarded by the thermal stations. However, no incipient creep damage was discovered and the test program was redirected to examine artificially damaged bolt materials. The final analysis, using laboratory creep test data, indicated that either reheat treatment or Hot Isostatic Processing could restore the bolt materials to the original specifications.

3.10 Corrosion Fatigue

3.10.1 Crack Initiaton

Corrosion fatigue damage on the waterside is a major cause of forced outage in thermal boilers. The main objective of this work is to provide information which can improve operation procedures to reduce the incidence of corrosion fatigue cracking. The essential hardware for the static flow autoclave system is all functionally ready for commissioning and preliminary testing. However, the test program was deferred due to the recurring hydraulic problem in the MTS.

Baseline tests in an inert nitrogen atmosphere were also planned. The AC potential drop system was applied to the smooth low cycle fatigue specimen and the initial results indicated the excellent signal stability was achieved during load cycling. The change in the potential drop value and the specimen's elongation can be used as the criteria for crack initiation in both baseline and autoclave tests. The experimental program was delayed due to unavailability of personnel and the data logging program was not developed as planned. However, some familiarity with the new operating system of the multitasking computer system was accomplished.

3.10.2 Crack Propagation

The program is funded by CEA and the main purpose of this investigation is to generate crack growth data to complement the research effort carried out on crack initiation.

Most of the time was spent on the selection and assembly of equipment to build a static autoclave system at the University of Toronto. The laboratory space for a 7.6L autoclave vessel mounted onto a 500 kN four-column MTS system was made ready. Water chemistry analysis was done by offline analysis of water samples collected by bleeding the process water through a high pressure valve. Considerable effort was spent on the titration method to measure dissolved oxygen in boiler water, following the recomended ASTM 0888 procedures. The sensitivity of this technique was reported to be about $\pm$ 2 ppb. An in-situ electrode based on the ionizaton potential using an Americium 241 source was also chosen for preliminary trials to measure the electrochemical potential near the cracking surface on the crack growth specimen. The crack growth rate will be determined by a high temperture LVDT using the compliance method.

3.11 Short-Term Work

Two investigations were undertaken for CTS, the first to ascertain the extent and mechanism of cracking which had caused steam leakage in a Lambton reheater header and which had been shown to be present in all the SH and RH headers at the station. It was shown that the damage was due to thermal shocks and a simple fatigue analysis agreed with the operating history as deduced by CTS. A similar examination of a thicker-walled SH header later revealed a similar form of damage. In neither header was there any incidence of a creep contribution to the cracking process.

The second investigation was on water-wall tubing from Nanticoke, from a region of the Unit 1 boiler with a history of over-temperature induced ruptures. It was shown that the tubes had experienced long-term moderate overheating and an effective operating temperature was determined based on creep and microstructural damage. The damage was confined to a narrow zone and was presumed to have been caused by a well-defined pattern of steam blanketing.

4.0 1985 PROGRAMS

4.1 Hydrides And Hydride Cracking

4.1.1 Hydride Blisters

Technical administration of the TRAC program is expected to take a considerable effort in 1985.

Blister growth tests will continue. Initially the emphasis will be on analysis of experiments performed to date. Deuteride blisters will also be grown and these will be analysed at Queen's University to produce the concentration profiles of deuterium within the blisters. Additional blister growth work will examine effects of thermal cycling, hydrogen ingress and blister dissolution.

Blister cracking studies will be carried out in conjunction with the NDFE Section. Some preliminary tests have been completed. The direction for future work is yet to be established.

4.1.2 Delayed Hydride Crack Growth Studies

The effect of hydride morphology, thermal history and variability of pressure tubes on delayed hydride cracking velocity in Zr-2.5 Nb pressure tubes will be evaluated. Small compact tension specimens and some constant K specimens will be used to measure

DHC velocity at 250°C and 290°C. Crack growth will be monitored by DC potential drop. The following parameters will be examined:

1) Hydride orientation and spacing - radial or circumferential hydrides with different hydride spacings.

2) Thermal history - thermal cycling from 300°C, direction of temperature approach.

3) Variability in pressure tubes - manufacturing processes (eg β quenching); different tensile properties.

4) Effect of increasing hydrogen concentration during testing when the test temperature is approached from below.

4.1.3 Fuel Bundle Scratch Test

It has previously been demonstrated that fuel bundle scratches are not likely to crack existing radial hydrides and initiate DHC. However, some fairly deep fuel bundle scratches were observed in some Bruce channels which might act as stress concentrators for DHC. In this program, four-point bend loading rigs will be used to apply sufficient circumferential tensile stress in hydrided Zr-2.5 Nb pressure tube sections to form radial hydrides at the ID surface. The specimens will be scratched by passing fuel bundles over them. The scratched specimens will be thermally cycled under stress to determine if DHC can be initiated.

4.1.4 Fracture Mechanisms Of Hydrided Pressure Tubes

Zircaloy pressure tube material containing radial axial hydrides displayed a sharp brittle to ductile behaviour as a function of temperature in both uniaxial tensile tests and compact tension tests. The transition temperature is affected by hydrogen concentration and the type of loading. A detailed SEM fractographic examination will be performed to determine the conditions that lead to the observed fracture mechanisms.

4.1.5 Hydride Crack Growth In PHT Environment

A summary report on experimental results obtained at OHRD will be completed and the future contribution that OHRD can provide will also be reviewed to prevent any duplication. AECL-RC (WNRE) will be generating autoclave data with externally loaded compact tension specimens.

4.1.6 Crack Initiation in Pressure Tube Materials

The first modified bending rig will be tested and strain gauging of the curved four-point bend secton will verify the amount of stress relaxation estimated from published data. The test matrix will include variables such as hydrogen content, stress level and thermal cycling. The preparation of more four-point bend rigs and metallography to determine the hydride morphology will require that most of the technical effort be committed to this program.

The load following experiments will require the hydriding of tensile specimens for tension to tension fatigue loading. A hypothetical load cycle will be chosen after consultation with the operators and stress analysts. For comparison, crack initiation data under dead load conditions will be required. The potential drop system will be used to detect crack initiaton and a dedicated instrument will be assembled.

The above program requires continuous data collection and analysis. A multitasking computer system will therefore be selected and established to monitor the experiments and to complement the existing data collection facility for delayed hydride cracking.

4.2 Irradiation Deformation

4.2.1 Irradiaton Growth of Pressure Tube Materials

It is intended to perform irradiation growth tests on materials with characterized structure, current and TG3 pressure tubes to anticipated end-of-life fluence. Irradiation will be carried out at an average fast neutron flux of $\sim 7 \times 10^{17}$ $n.m^{-2}$ s^{-1} at temperatures of 280, 310 and 350°C. Most samples will be tested isothermally to investigate the temperature dependence of growth, whilst others will be switched from one irradiation temperature to another in an attempt to assess the effect of temperature cycling. In this way a description of irradiation growth behaviour as a function of individual structural parameters should be developed.

4.2.2 Evaluation of the Out Reactor Creep Properties of Zr-2.5 Wt % Nb

Uniaxial, constant stress, creep tests will be carried out on current and TG3 pressure tube materials at accelerated temperature and/or stress conditions compared to service. Extrapolation of these data will be attempted using the projection concept to assess the contribution to plant deformation of "thermal" creep.

4.2.3 Correlation of Out-Reactor Creep Properties Under Uniaxial and Multiaxial Stress Conditions

Isothermal and cyclic tests will be undertaken on sections of current and TG3 pressure tubes loaded by internal pressure. Attempts will be made to correlate uniaxial and multiaxial behaviour and to evaluate the effect of cycling on the deformation rate and rupture life and ductility.

4.2.4 To Determine the Irradiation Creep Characteristics Of Zr-2.5 WT % Nb Material Irradiated in the Dido Reactor

Interpretation of data from irradiation experiments is often complicated by the fact that the contribution to the total strain from individual mechanisms is unknown. Irradiation creep and stress relaxation experiments have been planned in collaboration with AECL testing material from the irradiation growth study in progress at Harwell. In this way it is anticipated that the factors affecting both creep and growth can be determined, and thus a description for in-reactor pressure tube deformation can be established.

4.2.5 Correlation of Residual Stress with Irradiated Growth of Zr-2.5 WT % Nb

A program of internal stress measurement on pressure tube material has been discussed with AECL. It is suggested that variatons in internal stress may control in-reactor performance. This concept will be examined by undertaking internal stress measurements on selected samples from the current growth study in progress at Harwell.

4.2.6 To Relate In-Service Behaviour with Metallurgical Structure

Plant information will be examined in an attempt to assess relationships for prediction of pressure tube behaviour.

4.3 Materials Properties For CANDU Reactor Core Component Alloys

4.3.1 Transient Deformation Behaviour

Test procedure and associated computer software packages available for executing computer-controlled transient deformation testing are now quite comprehensive. The main area of improvement lies in the development of accessory equipment which will enable testing in vacuum, inert gas or steam environments. In 1985, we anticipate only a limited number of transient deformation tests.

These tests will be carried out when the demand arises to fill in gaps in the existing data base for transient deformation behaviour.

4.3.2 Fundamental Studies of Elevated Temperature Deformation Behaviour

The experimental data needed to develop more general purpose deformation equations for Zr-2.5 wt % Nb and Zr-2 PT material and Zr-2 CT material were increased significantly in the past year. In 1985, we plan to continue to increase the scope of the above experimental data base. Experience tells us that the development of appropriate constitutive equations requires a better understanding of the basic deformation mechanisms operative in Zr-alloys used in CANDU power reactors. We plan to acquire some of the required understanding by carrying out a series of well-characterized tensile tests followed by examining the deformed material using transmission electron microscopy (TEM).

4.3.3 Biaxial Deformation

In the first quarter of 1985, we will concentrate our efforts on completing the test program outlined in our current CANDEV-funded project (84/85) with AECL-WNRE. The above test program entails performing six(6) biaxial tests to determine the nature of circumferential temperature gradients developed in tube samples partially filled with water.

We anticipate that our proposal for a CANDEV-funded project for 85/86 will be approved. The main objective of the new biaxial test program is to establish quantitatively what combinations of internal pressure and temperature are critical in slowing down or significantly suppressing the deformation of Zr-2.5 Nb PT's at elevated temperatures. A series of eight (8) biaxial tests is planned.

We will also continue to investigate other possible applications for the BTF. Applications requiring rapid heating and/or biaxial deformation are ideal for the BTF.

4.3.4 Materials Data for CANDU Zircaloy-4 Fuel Cladding

Two test programs designed to produce appropriate materials data for Zr-4 fuel cladding are planned for 1985.The first project will entail the characterization of end cap/sheath welds, bearing pad braze heat affected zones (HAZ's) and weld HAZ's in CGE Bruce-type fuel pencils. The second program (much larger in scope) will involve producing materials data suitable for use in

analysis of CANDU reactor fuel cladding integrity after exposure to oxidation in the temperature range 873 - 1223 K. We anticipate that both of the above projects will be funded by CNS.

4.4 Transmission Electron Microscopy

4.4.1 Dislocation Substructure

TEM studies of dislocation substructure in various pressure tube materials will be continued in 1985 with a view to understanding their role on irradiation and strengthening behaviour. It is intended to further investigate sub-boundaries which contain <c> and <a+c> dislocations. The main research will be focussed on the more complete analysis of these boundaries and the electron diffraction control of the dislocations in them.

4.4.2 TEM Studies of Irradiated Zr-2.5 % Nb Alloys

The developed dislocation substructure composed of dislocations with different Burgers vectors should have an effect on irradiation growth. The presence of different types of dislocations and their spatial distribution influences irradiaton growth by altering the manner in which irradiation produced point defects are partitioned among various sinks. A number of samples of various Zr-2.5% Nb pressure tube materials have been subjected to neutron irradiation in the Dido reactor at Harwell. Post irradiation TEM investigations of these samples should provide useful information on the effects of neutron irradiation on dislocation substructure, phase stability and the nature of neutron damage in pressure tube materials.

4.4.3 Hydride Precipitation

Continue the program to study the role of internal stresses on hydride precipitation in zirconium alloys. All "preparations" are completed and extensive TEM investigations will be performed on hydride precipitation as well as on development of dislocation substructure in the Zircaloy samples with known internal (grain to grain) residual stresses. We expect that these studies will be continued throughout 1985. The first study will be performed on the coarse-grained Zircaloy and if successful, this type of experiment could be extended at a later date to the fine-grained microstructures of Zircaloy or Zr-2.5% Nb pressure tube alloys.

4.4.4 LOCA Studies

Further TEM characterization of dislocation substructure and phase morphology related to high temperature deformation in Zr-2.5% Nb pressure tube alloys is planned.

4.4.5 Studies Using Scanning Transmission Electron Microscopy (STEM)

It was proposed in 1984 to study stability of the arrays of precipitates in the Aℓ -3.6% Cu single crystals using McMaster's STEM. The proposal is still active and there is also the possibility to use this instrument to study hydrides in Zirconium alloys. These studies will be done in collaboration with Professor G.R. Purdy, Department of Metallurgy and Materials Science, McMaster University.

4.5 Residual Life Studies

Testing will continue on 2¼ Cr 1 Mo steel to provide the matrix of information necessary to fully characterize the creep behaviour of this material.

The exchange of information initiated with the CEGB will be ongoing.

4.6 Dissimilar Metal Weld Testing

It is intended to extend the program of critical tests on DMW's so that the current life prediction model can be assessed at a range of temperatures.

4.7 High Temperature Crack Growth

The 1985 test program will concentrate on the completion of the hyperbolic sine model and the linear damage methodology. In particular, test data on different loading ratio and temperature will be required. To optimize the available resources, information from the open literature should be examined in depth and applied to the in-house data base. The CEGB creep data for 565°C can probably supplement the existing creep fatigue information and provide a conservative data base for predicting crack growth behaviour at the actual steam temperature of 540°C. As the weld and heat affected zone microstructure, when compared to the parent material, have lower resistance to creep fatigue damage, the main thrust of the test program will be directed to the behaviour of these structures. To measure the effect of geometric constraint on crack growth, tests on thin cantilever-cracked specimens will also be required.

4.8 Corrosion Fatigue

4.8.1 Crack Initiation

The major effort is expected to be spent on the commissioning of the autoclave system. The baseline test matrix will be completed and, hopefully, some autoclave tests will be carried out. The experimental difficulties to be encountered are the implementation of an ionization electrode and the detection of crack initiation by the AC potential drop method. The research program may fall short of generating sufficient data for structural integrity evaluation due to lack of resources; however the framework for carrying out state-of-the-art investigation will be established. The multitasking data collection and analysis facility will also be completed.

4.8.2 Crack Propagation

The project team at the University of Toronto will begin crack growth tests on 25 mm thick WOL type of specimen. The test variables will include different frequency, hold time, loading ratio and dissolved oxygen. Data analysis will be carried out to establish a relationship between the crack growth rates and the Stress Intensity Factor range, and a draft report for the CEA will be initiated at year end.

4.9 Bolting

Main emphasis in this limited budget CTS-funded program will be on the Durehete 1055 12 Cr-Mo-V material. It is hoped that the work held up in 1984 because of staffing constraints will proceed, particularly in terms of creep tests, to determine the long term properties of the replacement material supplied by Atlas Steel. Also of concern to CTS are the relevance of the NEI Parsons equivalent lifetime for bolts and methods of extending bolt life; this is particularly important for Nanticoke units. Other aspects which may be addressed in a limited fashion are the effects of grain size and residual element content on creep properties.

The work on 12Cr material has lower priority but potential areas are assessment of methods to determine rate of in-service damage accumulation and selection of the best microstructure for service application.

5.0 SUMMARY

The Materials Integrity Project will continue to consider the assessment of CANDU core components integrity as its major priority. Resource levels for these studies are somewhat limited and we cannot totally re-deploy resources currently working on thermal plant problems. In fact, the Materials Integrity Project is actively pursuing an EPRI contact related to the assessment of residual life in thermal plants. This action is a result of a need to attract revenue and on the world level there is money for thermal plant problems but not for CANDU related problems. This highlights the unique situation that Ontario Hydro is faced with, ie it must generate its own information on CANDU as there are no other utilities or organizations in the world which are as heavily committed as Ontario Hydro to pressure tube reactors.

6.0 LIST OF REPORTS IN 1984

a) Class A

84-41-K "A Facility to Study Crack Growth Behaviour at Elevated Tempertures" (W.K.Lee and R.E.Irwin).

84-49-K "Crack Growth Modelling for 2.1/4 Cr 1 Mo Steel" (W.K. Lee).

84-85-K "Deformation Behaviour of Zr-2.5 wt % Nb Pressure Tube Material Under Constant Strain Rate Conditions in the Temperture Range 773-973 K" (E.T.C. Ho and S.R. MacEwen)

84-86-K "FuelBundle Scratch Tests of Zr-2.5 wt % Nb Pressure Tube Containing Radial Axial Hydrides (F.Worm and G.K.Shek).

84-100-K "DeformationBehaviour of Zr-2.5 Wt % Nb Pressure Tubes Under Internal Pressurizaton and Ramp Temperature Conditions" (E.T.C. Ho and A. Donner).

84-278-K "On the Dislocation Substructure in Zr-2.5 wt% Nb Pressure Tubes (V.Perovic and G.C.Weatherly).

84-279-K "Axial Tensile Properties of CANDU Reactor Grade Zircaloy-2 Calandria Tube Material in the Temperature Range 295-573 K" (E.T.C. Ho and M.J. McGraw).

84-307-K "Metallurgical Examination of Reheater Outlet Header, Lambton GS, Unit 3" (H.J.Westwood and J.Parker).

84-354-K "Transverse Tensile Properties of Zr-2.5 wt% Nb Pressure Tube Material in the Temperature Range 295-723 K" (E.T.C. Ho and M.J. McGraw).

84-366-K "Metallurgical Examination of Overheated Water-wall Tubes - Nanticoke GS, Unit 1" (H.J.Westwood).

84-381-K "Biaxial Deformation Behaviour of Zr-2.5 wt% Nb Pressure Tubes at Low Internal Pressures and Elevated Temperatures in a Steam Environment (E.T.C.Ho and A.Donner).

84-392-K "Comparison of Zircaloy-2 Pressure Tube Burst Test with Curved Double Torsion Results" (P.H. Davies and G.K. Shek).

Class B

M84-8-K "Failure Analysis of Radiant Superheater Tube, Thunder Bay, Unit 1" (W.K. Lee).

M84-41-K "A Faclity to Study Crack Growth Behaviour at Elevated Temperature" (W.K.Lee and R.E.Irwin).

M84-48-K "Variation of Ultimate Tensile Strength with Temperature in CANDU Reactor Grade Zircaloy-2 Calandria Tube Material at Applied Strain Rates in the Vicinity of 3×10^{-1}, s^{-1}" (E.T.C. Ho and M.J. McGraw).

M84-53-K "Examination of Hydride Morphology in a Zircaloy-2 Overextended Rolled Joint" (G.K. Shek and H.Seahra).

M84-63-K "Examination of Transition Weld Samples from Unit 5, Lakeview GS" (J.D. Parker)

M84-71-K "Failure Analysis of Reheater Tubes, Lakeview, Unit 5" (W.K. Lee).

M84-78-K "A Proposal for the Evaluation of Thick-Ended Zr-2.5 Nb Replacement Tubes for Pickering Units 1 & 2 Reactors" (G.K. Shek)

M84-98-K "Evaluation of Thick-Ended Zr-2.5 Nb Replacement Pressure Tubes for Pickering Units 1 and 2 Reactors: Progress No 1" (G.K. Shek)

M84-157-K "Integrity of CANDU Reactor Zircaloy-4 Fuel Cladding after Oxidation in the Temperature Range 873-1223 K: A Proposal" (E.T.C. Ho).

7.0 PUBLICATIONS

"Ontario Hydro Experience with Dissimilar Metal Welds in Boiler Tubing" -T.P. Byrne and R.B. Dooley, J.D. Parker, EPRI/MPC Seminar, February 23 1984 - New Orleans.

"The Behaviour of High Temperature Fasteners in Electricity Generating Plant", J.D. Parker, International Conference on "Creep and Fracture of Engineering Materials and Structures", April 1-6, 1984,- Swansea.

"Remaining Life Estimation of High Temperture Boiler and Turbine Components", D.Sidey, R.B.Dooley and J.D.Parker, EPRI Workshop "Fossil Plant Life Extension" June 12-15, 1984 - Washington.

"Prediction of the Service Performance of Boiler Components Operating under Creep Conditions", D.Sidey, R.B.Dooley and J.D.Parker, Joint Power Conference, October 1-4, 1984 - Toronto.

"The Behaviour of Ferritic Weldments in Thick Section 1/2 Cr 1/2 Mo 1/4V Pipe at Elevated Temperature", M.C.Coleman (CEGB Marchwood, UK), D.J.Walters (CEGB, Berkeley,UK) and J.D.Parker, Journal of Pressure Vessels and Piping.

"A Sampling Procedure for Estimating the Residual Life of Fossil-Fuelled Plant Boiler Tubing", M.D.C. Moles, H.J. Westwood and W.K. Lee, Canadian Metallurgical Quarterly.

"The Effect of Stress on Orientaton of Hydrides in Zirconium Alloy Pressure Tube", M.Leger and A.Donner - submitted to Canadian Metallurgical Quarterly.

"The Nucleation of Hydrides in a Zr-2.5% Nb Alloy", V.Perovic and G.C. Weatherly, Journal of Nuclear Materials, Vol 126, p 160, 1984.

"Characterization of Substructure in Zr-2.5% Nb Pressure Tube Alloys", V.Perovic, R.G.Fleck and G.C.Weatherly, presented at CIM Conference, Quebec City, August 1984 - to be published in Canadian Metallurgical Quarterly.

"An Evaluation of the Use of Fracture Mechanics Parameters to Describe Creep-Fatigue Crack Growth in 2.1/4 1 Mo Steel", presented at the 23rds Conference of Metallurgists, Quebec, August 19 - 22, 1984.

8.0 CONFERENCES

EPRI/MPC Seminar "Solutions to Problems with Dissimilar Metal Weldments in Fossil-Fired Power Plants", New Orleans, February 23-24, 1984.

International Conference on "Creep and Fracture of Engineering Materials and Structures", Swansea, April 1-6, 1984.

34th Canadian Metal Physics Conference, Kingston, June 6-8, 1984.

"Prediction of Long-Term Creep Behaviour", Stanford Univerity, Palo Alto, November 12, 1984.

"Residual Life and Life Extension Techniques for the Fossil Fired Plant", EPRI, Palo Alto, November 13, 1984.

"Characterization of Pressure Tube Deformation Behaviour Relevant to Reactor Safety Analyse under LOCA Conditions", Metallurgical Research Departmental Seminar.

"Mechanical Properties of Zirconium Alloys at Elevated Temperatures" - Invited talk at AECL-CO, Meadowvale.

"New Direction in Crack Initiation" - presented at 1st Annual Technical Review Meeting on Fuel Channel Research, held at Whiteshell Nuclear Research Establishment, September 25-27, 1984.

Seminar on Creep and Growth, Orangeville, March 28-29, 1984.

Seminar on Hydrogen in Metals and Metal Hydrides, University of Toronto, March 16, 1984.

Visiting Lectures of Dr. L.M. Brown (Cavendish Laboratory, Univerity of Cambridge, UK) on Electron Microscopy, McMaster Univerity, December 10-13, 1984.

CIM Annual Meeting, Quebec City - 3 papers presented (1 for P.Mayer and A.Manolescu) - M.Leger.

Talk to Metallurgy Club, Univerity of Toronto - "Pickering Pressure Tube Failure Analysis" - M.Leger.

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